Kepler Asteroseismology Program:
Introduction and First Results

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ABSTRACT

Asteroseismology involves probing the interiors of stars and quantifying their global properties, such as radius and age, through observations of normal modes of oscillation. The technical requirements for conducting asteroseismology include ultra-high precision measured in photometry in parts per million, as well as nearly continuous time series over weeks to years, and cadences rapid enough

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to sample oscillations with periods as short as a few minutes. We report on results from the first 43 days of observations in which the unique capabilities of *Kepler* in providing a revolutionary advance in asteroseismology are already well in evidence. The *Kepler* asteroseismology program holds intrinsic importance in supporting the core planetary search program through greatly enhanced knowledge of host star properties, and extends well beyond this to rich applications in stellar astrophysics.

Subject headings: Review (regular)

1. INTRODUCTION

The *Kepler Mission* science goals and initial results in the core planet-detection and characterization area, as well as the mission design and overall performance, are reviewed by Borucki et al. (2010), and Koch et al. (2010).

Asteroseismology is sometimes considered as the stellar analog of helioseismology (Gough et al. 1996), being the study of very low amplitude sound waves that are excited by near-surface, turbulent convection, leading to normal-mode oscillations in a natural acoustical cavity. The Sun, when observed as a star without benefit of spatial resolution on its surface, shows $\sim$ 30 independent modes with white light amplitude of a few parts per million (ppm) and periods of 4 – 8 minutes. In many cases stars with stochastically driven oscillations may deviate strongly from solar size, as in the case of red giants detailed below. For our purposes, however, we will broaden the definition of asteroseismology to also include the many types of classical variable stars, e.g. Cepheids, famous for helping to establish the scale of the universe (Hubble & Humason 1931).

There are two primary motivations for performing asteroseismology with *Kepler*, which is primarily a planet-detection and characterization mission (Borucki et al. 2010). First, knowledge of planet properties is usually limited to first order by knowledge of the host star, e.g. *Kepler* easily measures the ratio of planet to star size through transit depths. Turning this into an absolute size for the planet requires knowledge of the host star size which, in favorable cases, asteroseismology is able to provide better than any other approach – in many cases radii can be determined to accuracies near 1%. Second, the instrumental characteristics already required for the exquisitely demanding prime mission (Borucki et al. 2010; Koch et al. 2010) can readily support the needs of seismology at essentially no additional cost or modification, thus promising strong science returns by allocating a few percent of the observations to this exciting area of astrophysics.

Oscillations in stars similar to the Sun, which comprise the primary set for the planet detections, have periods of only a few minutes and require use of the Short Cadence (SC) mode with 58.8-second effective integrations. Many of the classical variables may be studied well with the more standard Long Cadence (LC) mode, which has 29.4-minute effective integrations.

Kepler comes at a propitious time for asteroseismology. The forerunner missions MOST (Matthews 2007), and especially CoRoT (Baglin et al. 2009; Michel et al. 2008), have started our journey taking space-based asteroseismology from decades of promise to the transformative reality we realistically expect with *Kepler*. The most salient features of the *Kepler Mission* for asteroseismology are: (a) a stable platform from which nearly continuous observations can be made for months to years, (b) cadences of 1 and 30 minutes which support the vast majority of asteroseismology cases, (c) a large 100 square degree field of view providing many stars of great intrinsic interest, (d) a huge dynamic range of over a factor of 10,000 in apparent stellar brightness over which useful asteroseismology (not always of the same type of variable) can be conducted, and (e) exquisite precision that in many cases is well under one ppm for asteroseismology purposes. Initial data characteristics for SC (Gilliland et al. 2010) and LC (Jenkins et al. 2010) have been shown to support results that nearly reach the limit of Poisson statistics.

2. SUPPORT OF EXOPLANETARY SCIENCE

The *Kepler Input Catalog* (KIC) (Koch et al. 2010) provides knowledge ($30 - 50\%$ errors on stellar radii) of likely stellar properties for ~ 4.5 million stars in the *Kepler* field of view at a level of accuracy necessary to specify the targets to be observed. One likely application of asteroseismology will follow from quantification of stellar radii to more than an order of magnitude better than this for a few thousand giant stars, and several hundred dwarfs, which can then be used to test the KIC entries, and quite possibly provide the foundation for deriving generally applicable improvements to the calibrations enabling redefined entries for the full catalog.

Some 15% of the KIC entries were not classified, thus no radius estimates were available to support selection of stars most optimal for small-planet transit searches. In Q0 (May 2009) and Q1 (May – June 2009) a total of about 10,000 such unclassified stars brighter than Kepler-mag = 13.8 were observed for either 10 and/or 33 days respectively. An early application of asteroseismology was to identify stars in this unclassified set that are obviously red giants, a well-posed exercise given the quality of *Kepler* data (Koch et al. 2010), and thus allow these to be dropped from further observation in favor of bringing in smaller, and

photometrically quieter stars.

At a more basic level asteroseismology can play an important role in quantifying knowledge of individual planet host candidates. In particular, by showing that the stellar radius is significantly greater than the catalogued value, we can rule out a planetary candidate without the need to devote precious ground-based resources to measuring radial velocities. One such case is the Kepler Object of Interest[1] (KOI) identified as KOI-145, whose light curve shows a transit. The host star KIC-9904059 has a tabulated radius of just under 4 $R_\odot$, adjusted to 3.6 $R_\odot$ with addition of ground-based classification spectroscopy[2]. This radius allows a transit light curve solution with a transiting body below 1.6 R_J, hence the KOI designation.

Figure 1 shows that KIC-9904059 displays oscillations characteristic of a red giant star. The pattern of peaks in the power spectrum follows the spacing expected from the asymptotic relation for low-degree p modes (restoring force is pressure for sound waves) which may be given as (Tassoul 1980; Gough 1986):

$$\nu_{nl} \approx \Delta\nu(n + l/2 + \epsilon) - D_0 l(l + 1). \tag{1}$$

Here $\Delta\nu = (2 \int_0^R dr/c)^{-1}$ is the so-called large separation, which corresponds to the inverse of the sound travel time across the stellar diameter. In this notation n represents the number of nodes in a radial direction in the star for the standing sound waves, and l is the number of nodes around the circumference. For stars observed without spatial resolution only $l = 0$, 1, and 2 modes are typically visible in photometry, since the higher-degree modes that are easily visible on the Sun average out in disk-integrated measurements. It can be shown that $\Delta\nu$ scales as the square root of the stellar mean density, and more precise determinations of $\langle \rho_* \rangle$ follow from using stellar evolution models (Christensen-Dalsgaard et al. 2010). The ϵ term captures near-surface effects, while D_0 represents the so-called small separation, which between $l = 0$ and 2 we will refer to as: δ_{02}. In main-sequence stars this small separation is sensitive to the sound speed in the stellar core, hence the evolving hydrogen content, and helps constrain stellar age.

The asteroseismic solution for KOI-145 yields $\Delta\nu = 11.77 \pm 0.07$ μHz, with maximum power at a frequency $\nu_{\max}$ of 143 ± 3 μHz, and an amplitude of 50 ppm for the radial modes,

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[1]The project uses these numbers for the internal tracking of candidates (Borucki et al. 2010), which are not synonymous with claimed detections of planets.

[2]Based on Spectroscopy Made Easy – Valenti & Piskunov 1996 – analysis by Debra Fischer using a spectrum of KOI-145 obtained by Geoff Marcy at the W. M. Keck Observatory which gives $T_{\rm eff} = 4980 \pm 60$, log(g) = 3.47 ± 0.1, and [Fe/H] = -0.02 $\pm$ 0.06.

all in excellent agreement with canonical scaling relations. The $\Delta\nu$ corresponds to $\langle\rho_*\rangle =$ 0.0113 ± 0.0001 g cm^{-3} (Kjeldsen, Bedding & Christensen-Dalsgaard 2008) and, using the spectroscopic constraints on stellar temperature and metallicity, yields solutions for mass and radius of 1.72 ± 0.13 M$_\odot$ and 5.99 ± 0.15 R$_\odot$ following the procedure of Brown (2009).

Adopting the larger asteroseismic radius of 5.99 R$_\odot$, Figure 1 shows the light curve for KOI-145 (only one eclipse has been seen so far) and an eclipse solution indicating that the transiting body has a radius of $0.45^{+0.11}_{-0.07}$ R$_\odot$ assuming an orbital period of 90 days (the minimum currently allowed). Assuming a longer orbital period allows yet larger values for the radius of the eclipsing body. In this case, asteroseismology securely sets the radius of the host star and forces the solution for the eclipsing object firmly into the stellar domain. The 3-σ lower-limit to the transiting body radius is 3.4 R$_J$. More detailed analyses await fixing the orbital period from repeated eclipses.

In Figure 2a the filled symbols show the observed frequencies in KOI-145 in a so-called échelle diagram, in which frequencies are plotted against the frequencies modulo the average large frequency spacing (but note that the abscissa is scaled in units of $\Delta\nu$). The frequencies were extracted by iterative sine-wave fitting in the interval $\nu_{max} \pm 3\Delta\nu$ down to a level of 19 ppm, corresponding to 3.3 times the mean noise level in the amplitude spectrum at high frequency. The open symbols in Figure 2a show frequencies from a model in the grid calculated by Stello et al. (2009), after multiplying by a scaling factor of $r = 0.9331$ (Kjeldsen, Bedding & Christensen-Dalsgaard 2008).

An interesting feature of Figure 2a is the absence of a significant offset between observed and model frequencies for the radial modes. This contrasts to the Sun, for which there is a long-standing discrepancy that increases with frequency between observations and standard solar models, as shown in Figure 2b. This offset is known to arise from the inability to adequately model the near-surface effects (Christensen-Dalsgaard, Däppen & Lebreton 1988) and has been an impediment to progress in asteroseismology for solar-type stars, although an effective empirical correction has recently been found (Kjeldsen, Bedding & Christensen-Dalsgaard 2008) that allows accurate determination of the mean stellar density from $\Delta\nu$. As shown in Figure 2 a, the offset between the measured and theoretically computed frequencies for $l = 0$ modes in KOI-145 is very small, suggesting some simplification in interpretations for red giants if this surface term can be generally ignored. Other factors for red giant oscillations, however, are already significantly more complex than in the Sun, as argued in the recent theoretical analysis of Dupret et al. (2009). In particular, less efficient trapping of the modes in the envelope for red giants on the lower part of the red giant branch can lead to multiple non-radial modes, especially for $l = 1$ (Dupret et al. 2009). We see this in KOI-145 and also in other red giants observed by *Kepler* (Bedding et al. 2010).

The asteroseismic solution for HAT-P-7 by Christensen-Dalsgaard et al. (2010) illustrated in Figure 3 demonstrates the great potential for refining host star properties. The stellar radius is determined to be 1.99 ± 0.02 R$_\odot$, an order of magnitude gain in confidence interval from solutions based on ground-based transit light curve solutions by Pál (2008), with an age of 1.9 ± 0.5 Gyr. Such improvements to host star knowledge, thus ultimately planet size and density (when radial velocities provide mass) are critically important for informing studies of planet structure and formation.

3. INDEPENDENT STELLAR ASTROPHYSICS

The mission as a whole will benefit from enhanced knowledge of stellar structure and evolution theory. This can best be advanced by challenging theory with detailed observations of stellar oscillations across a wide range of stellar types. Supporting this goal has led to devoting 0.8% from the available LC target allocations (still a very healthy number of 1,320 stars) to a broad array of classical variables. These LC targets are usually large stars with characteristic periods of variation of hours, to in extreme cases months or even years, and hence are either massive and/or evolved stars. In addition, a set of 1,000 red giants selected to serve as distant reference stars for astrometry (Monet 2010) provide enticing targets for LC-based asteroseismology. A number of stellar variables, including, of course, close analogs of the Sun can only be probed with use of the SC (1-minute) observations, on which a cap of 512 targets exists. Most of these SC slots are now being applied to a survey of asteroseismology targets rotated through in one-month periods. After the first year a subset of these surveyed targets will be selected for more extended observations. As the mission progresses, a growing fraction of the SC targets will be used to follow up planet detections and candidates, for which better sampling will support transit timing searches for additional planets in the system (Holman & Murray 2005) and oscillation studies of the host stars.

Asteroseismology with *Kepler* is being conducted through the Kepler Asteroseismic Science Consortium (KASC)[3], whose $\sim$250 members are organized into working groups by type of variable star. So far data have been available from the first 43 days of the mission

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[3]The Kepler Asteroseismic Investigation (KAI) is managed at a top level by the first 4 authors of this paper. The next level of authorship comprises the KASC working group chairs, and members of the KASC Steering Committee. Data for KASC use first passes through the STScI archive for *Kepler*, then if SC is filtered to remove evidence of any transits, and then is made available to the KASC community from the Kepler Asteroseismic Science Operations Centre (KASOC) at the Department of Physics and Astronomy, Aarhus University, Denmark. Astronomers wishing to join KASC are welcome to do so by following the instructions at: http://astro.phys.au.dk/KASC/.

for ∼2300 LC targets, some selected by KASC and some being the astrometric red giants. The SC data have only been made available for a small number of targets (Chaplin et al. 2010). The remainder of this paper reviews the science goals for *Kepler* asteroseismology and summarizes some of the first results.

3.1. Solar-like Oscillations

Stars like the Sun, which have sub-surface convection zones, display a rich spectrum of oscillations that are predominantly acoustic in nature[4]. The fact that the numerous excited modes sample different interior volumes within the stars means that the internal structures can be probed, and the fundamental stellar parameters constrained, to levels of detail and precision that would not otherwise be possible (see, for example, Gough 1987). Asteroseismic observations of many stars will allow multiple-point tests to be made of stellar evolution theory and dynamo theory. They will also allow important constraints to be placed on the ages and chemical compositions of stars, key information for constraining the evolution of the galaxy. Furthermore, the observations permit tests of physics under the exotic conditions found in stellar interiors, such as those underpinning radiative opacities, equations of state, and theories of convection.

3.1.1. Main Sequence and Near Main Sequence Stars

Kepler will observe more than 1500 solar-like stars during the initial survey phase of the asteroseismology program. This will allow the first extensive "seismic survey" to be performed on this region of the color-magnitude diagram. On completion of the survey, a subset of 50 to 75 solar-like targets will be selected for longer-term, multi-year observations. These longer datasets will allow tight constraints to be placed on the internal angular momenta of the stars, and also enable "sounding" of stellar cycles via measurement of changes to the mode parameters over time (Karoff et al. 2009).

Figure 4 showcases the potential of the *Kepler* data for performing high-quality astero-seismology of solar-like stars from SC data (Chaplin et al. 2010). The left-hand panels show frequency-power spectra of three 9th-magnitude, solar temperature targets observed during

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[4]The solar-like oscillations are driven stochastically and damped by the vigorous turbulence in the near-surface layers of the convection zones, meaning the modes are intrinsically stable see, e.g. Goldreich & Keeley (1977), and Houdek et al. (1999).

Q1. All three stars have a prominent excess of power showing a rich spectrum of acoustic (p) modes. The insets show near-regular spacings characteristic of the solar-like mode spectra, and highlight the excellent S/N observed in the individual mode peaks. The sharpness of the mode peaks indicates that the intrinsic damping from the near-surface convection is comparable to that seen in solar p modes.

The p modes sit on top of a smoothly varying background that rises in power towards lower frequencies. This background carries signatures of convection and magnetic activity in the stars. We see a component that is most likely due to faculae – bright spots on the surface of the stars formed from small-scale, rapidly evolving magnetic field. This component is manifest in the spectra of the top two stars as a change in the slope of the observed background just to the low-frequency side of the p-mode envelope (see arrows). All three stars also show higher-amplitude components due to granulation, which is the characteristic surface pattern of convection.

The near-regularity of the oscillation frequencies allows us to display them in so-called échelle diagrams, in Figure 4. Here, the individual oscillation frequencies have been plotted against their values modulo $\Delta\nu$ (the average large frequency spacing – see Eq. 1). The frequencies align in three vertical ridges that correspond to radial, dipole, and quadrupole modes. By making use of the individual frequencies and the mean spacings we are able to constrain the masses and radii of the stars to within a few percent. The top two stars are both slightly more massive than the Sun (by about 5 %), and also have larger radii (larger by about 20 % and 30 % respectively). The bottom star is again slightly more massive than the Sun (10 %), and about twice the radius. It has evolved off the main sequence, having exhausted the hydrogen in its core. The ragged appearance of its dipole-mode ridge labeled "Avoided Crossing[5]" in Figure 4, is a tell-tale indicator of the advanced evolutionary state; the frequencies are displaced from a near-vertical alignment because of evolutionary changes to the deep interior structure of the star.

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[5]The effects are analogous to avoided crossings of electronic energy levels in atoms e.g., see Osaki (1975) and Aizenman, Smeyers & Weigert (1977). Here, evolutionary changes to the structure of the deep interior of the star mean that the characteristic frequencies of modes where buoyancy is the restoring force have moved into the frequency range occupied by the high-order acoustic modes. Interactions between acoustic and buoyancy modes give rise to the avoided crossings, displacing the frequencies of the dipole modes so that they no longer lie on a smooth ridge.

3.1.2. Red Giants

Red giants have outer convective regions and are expected to exhibit stochastic oscillations that are 'solar-like' in their general properties but occur at much lower frequencies (requiring longer time series). The first firm discovery of solar-like oscillations in a giant was made using radial velocities by Frandsen et al. (2002). However, it was only recently that the first unambiguous proof of nonradial oscillations in G and K giants was obtained, using spaced-based photometry from the CoRoT satellite (De Ridder et al. 2009). This opened up the field of red giant seismology, which is particularly interesting because important uncertainties in internal stellar physics, such as convective overshooting and rotational mixing, are more pronounced in evolved stars because they accumulate with age.

The extremely high S/N photometry of the *Kepler* observations brings red giant seismology to the next level. With the first 43 days of LC data we were able to detect oscillations with ν_{max} ranging from 10 μHz up to the Nyquist frequency around 280 μHz, as shown in Figure 5. The results include the first detection of oscillations in low-luminosity giants with $\nu_{\mathrm{max}} > 100\,\mu$Hz (Bedding et al. 2010). These giants are important for constraining the star-formation rate in the local disk (Miglio et al. 2009). In addition, *Kepler* power spectra have such a low noise level that it is possible to detect $l=3$ modes (Bedding et al. 2010) – significantly increasing the available asteroseismic information. The large number of giants that *Kepler* continuously monitors for astrometric purposes during the entire mission will allow pioneering research on the long-term interaction between oscillations and granulation. It is also expected that the frequency resolution provided by *Kepler* will ultimately be sufficient to detect rotational splitting in the fastest rotating giants, and possibly allow the measurement of frequency variations due to stellar evolution on the red giant branch.

3.2. Classical Pulsating Stars

Several working groups within KASC are devoted to the various classes of classical pulsators. The goals and first results are discussed below, ordered roughly from smaller to larger stars (i.e., from shorter to longer oscillation timescales), giving most emphasis to those areas in which scientific results have already been possible.

3.2.1. Compact Pulsators

The KASC Working Group on compact pulsators will explore the internal structure and evolution of stars in the late stages of their nuclear evolution and beyond. The two

main classes of targets are white dwarf stars (the ultimate fate of solar-mass stars) and hot subdwarf B stars – less-evolved stars that are undergoing (or just completing) core helium burning.

While compact stars are among the faintest asteroseismic targets, the science payoff enabled by continuous short-cadence photometry will be profound. Pulsations in these stars are far more coherent than for solar-like pulsators, so extended coverage should provide unprecedented frequency resolution, and may also reveal very low amplitude modes.

We will address several important questions about the helium-burning stage including the relative thickness of the surface hydrogen-rich layer (i.e. Charpinet et al. 2006), the role and extent of radiative levitation and diffusion of heavy elements (Charpinet et al. 2008), and the degree of internal differential rotation (Kawaler, Sekii & Gough 1999; Kawaler & Hostler 2005; and Charpinet, Fontaine & Brassard 2009). Even if these stars rotate extremely slowly, the high frequency resolution of *Kepler* data should reveal rotationally split multiplets. Asteroseismology can also probe the role of binary star evolution in producing these hot subdwarfs (Hu et al. 2008).

Similar questions about white dwarfs will be addressed, along with probing properties of the core such as crystallization (e.g. Metcalfe, Montgomery & Winget 2004; and Brassard & Fontaine 2005) and relic composition changes from nuclear evolution (see Winget & Kepler 2008, and Fontaine & Brassard 2008 for recent reviews of white dwarf asteroseismology).

3.2.2. Rapidly Oscillating Ap Stars

Rapidly oscillating Ap (or roAp) stars, with masses around twice solar, are strongly magnetic and chemically peculiar. They oscillate in high-overtone p modes, similar to those seen in the Sun (Kurtz 1982; Cunha 2007). Their abnormal surface chemical composition results from atomic diffusion, a physical process common in stars but most evident in Ap stars due to their extremely stable atmospheres. Since ground-based photometry only reveals a small number of oscillation modes in roAp stars, long-term continuous observations from space are needed to detect the large numbers of modes desirable for asteroseismology. This has been achieved for a few bright roAp stars using the MOST satellite, which found oscillation modes down to the level of 40 μmag (Huber et al. 2008). Since no roAp stars are present in the CoRoT fields, *Kepler*, with its 1 μmag precision should dramatically increase the number of detected oscillation modes – providing strong constraints on models of diffusion, magnetic fields, and the internal structure of roAp stars.

3.2.3. δ Sct and γ Dor Variables

Stars that exhibit both p modes (pressure-driven) and g modes (buoyancy-driven) are valuable for asteroseismology because they pulsate with many simultaneous frequencies. Theoretical calculations predict a small overlap in the H-R diagram of the instability region occupied by the γ Dor stars, which display high-order g modes driven by convective blocking at the bottom of the envelope convection zone (Guzik et al. 2000), and the δ Sct stars, in which low-order g and p modes are excited by the κ mechanism in the He II ionization zone[6]. Among the hundreds of known δ Sct and γ Dor variables, ground- and spaced-based observations have so far detected only a handful of hybrids (Handler 2009). The g modes in γ Dor stars have low amplitudes and periods of order one day, making them particularly difficult to detect from the ground. The *Kepler* Q1 data in LC mode have revealed about 40 δ Sct candidates and over 100 γ Dor candidates, among which we find several hybrid δ Sct – γ Dor stars (Grigahcène et al. 2010). These are young hydrogen-burning stars with temperatures of 6500–8000 K and masses of 1.5–2 $M_\odot$. Figure 6 shows an example.

The *Kepler* data, in conjunction with spectroscopic follow-up observations, will help to unravel theoretical puzzles for the hybrid stars. For example, *Kepler* should help us identify and explain the frequency of hybrid stars, discover previously unknown driving mechanisms, test theoretical predictions of the δ Sct and γ Dor oscillation frequencies, find possible higher-degree modes that fill in frequency gaps, and determine whether all hybrids show abundance peculiarities similar to Am stars as were noted in previously known hybrids. We should also learn about the interior or differential rotation of these objects via rotational frequency splittings. Perhaps just as interesting are those stars observed by *Kepler* that reside in the γ Dor or δ Sct instability regions that show no significant frequencies. Indeed, the discovery of photometrically constant stars at μmag precision would be very interesting. Studying *Kepler's* large sample of stars and looking for trends in the data will also help us better understand amplitude variation and mode selection.

Another unique possibility arising from the long-baseline, high-precision *Kepler* data is the ultimate frequency resolution it provides. The CoRoT mission has recently shown δ Sct stars to have hundreds and even thousands of detectable frequencies, with degrees up to $l \leq 14$ (Poretti et al. 2009). However, it has long been known that mode frequencies in δ Sct stars can be so closely spaced that years of data—such as that provided by *Kepler*—may be needed to resolve them.

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[6]The mechanism operates through perturbations to the opacity κ that blocks radiation at the time of compression in a critical layer in the star, heating the layer and contributing to driving the oscillation.

3.2.4. RR Lyr Stars

RR Lyr stars are evolved low-mass stars that have left the main sequence and are burning helium in their cores. Their "classical" radial oscillations with large amplitudes make them useful tracers of galactic history and touchstones for theoretical modelling (Kolenberg et al. 2010). Moreover, like Cepheids, they obey a period-luminosity-color relation which allows them to play a crucial role as distance indicators. Most RR Lyr stars pulsate in the radial fundamental mode, the radial first overtone, or in both modes simultaneously.

The phenomenon of amplitude and phase modulation of RR Lyr stars – the so-called Blazhko effect (Blazhko 1907) – is one of the most stubborn problems of the theory of radial stellar pulsations. With *Kepler* photometry, we will be able to resolve important issues, such as period variation, the stability of the pulsation and modulation, the incidence rate of the Blazhko effect, multiple modulation periods, and the existence of ultra-low amplitude modulation. Our findings should constrain existing (Dziembowski & Mizerski 2004) and future models. Moreover, *Kepler* may find second and higher radial overtones and possibly nonradial modes (Gruberbauer et al. 2007) in the long uninterrupted time series. Figure 7 shows two striking RR Lyrae light curves from the early *Kepler* data contrasting examples of a constant wave form and strongly modulated one.

3.2.5. Cepheids

Classical Cepheids are the most important distance indicators of the nearby Universe. Several candidates (Blomme et al. 2009) have been found in the *Kepler* field. Being long-period radial pulsators, Cepheids may show instabilities that have been hidden in the sparsely sampled, less accurate ground-based observations. *Kepler* also provides an excellent opportunity to follow period change and link it to internal structure variations due to stellar evolution. Period variation and eclipses will uncover binary Cepheids; faint companions may directly affect their role as distance calibrators (Szabados 2003).

The discovery of non-canonical Cepheid light variations is highly probable. Ultra-low amplitude (Szabó, Buchler & Bartee 2007) cases are in an evolutionary stage entering or leaving the instability strip (Buchler & Kolláth 2002), thus providing information on the driving mechanism and scanning the previously unexplored domains of the period-amplitude relation. Nonradial modes (Mulet-Marquis et al. 2007; Moskalik & Kolaczkowski 2009), and solar-like oscillations driven by convection, may provide a valuable tool to sound inner stellar structure, adding yet another dimension to asteroseismic investigations of Cepheids.

3.2.6. Slowly Pulsating B and β Cep Stars

Slowly pulsating B (SPB) stars are mid-to-late B-type stars oscillating in high-order g modes with periods from 0.3 to 3 days. These oscillations are driven by the κ mechanism acting in the iron opacity bump at around 200 000 K (Dziembowski, Moskalik & Pamyatnykh 1993; Gautschy & Saio 1993). Since most SPB stars are multi-periodic, the observed variations have long beat periods and are generally complex. The large observational efforts required for in-depth asteroseismic studies are hard to achieve with ground-based observations.

With the ultra-precise *Kepler* photometry of SPB stars spanning 3.5 years, it will be possible to search for signatures of different types of low-amplitude oscillations to probe additional internal regions. *Kepler* can resolve the recent suggestion that hybrid SPB/δ Sct stars exist (Degroote et al. 2009), thus filling the gap between the classical instability strip and the one for B stars with nonradial pulsations – which theory does not predict. The nature of the excess power recently found in β Cep and SPB stars (Belkacem et al. 2009; Degroote et al. 2009) can be quantified. *Kepler* should also allow us to investigate the stability of the periods and amplitudes, and to search for evolutionary effects in the more evolved B stars. *Kepler's* photometric capabilities will help us detect and explore both the deviations from regular period spacings predicted for g modes in the asymptotic regime (Miglio et al. 2008) and frequency multiplets induced by stellar rotation and/or magnetic fields. Finally, we will test the developing models that include the effects of rotation on g mode pulsations.

So far, some β Cep stars have been studied asteroseismically with data from intensive ground-based observational campaigns (Aerts 2008). These studies placed limits on convective core overshooting and demonstrated the presence of non-rigid internal rotation (Aerts et al. 2003), in addition to identifying constraints on the internal structure, opacities, and abundances (see, e.g., Pamyatnykh et al. 2004; Briquet et al. 2007; Daszyńska-Daszkiewicz & Walczak 2009). With the new level of precision provided by *Kepler*, we can go further, such as examining the suspected presence of solar-like oscillations in β Cep stars (Belkacem et al. 2009). The detection of more pulsation modes is key to detailed analyses of internal rotation. New methods using rotational mode splittings and their asymmetries have been developed by Suárez et al. (2009), and might help to test theories describing angular momentum redistribution and chemical mixing due to rotationally induced turbulence. The analysis of "hybrid" p and g mode pulsators will result in tighter constraints on stellar structure, particularly on opacities (Handler et al. 2009). This increased understanding of β Cep stars through asteroseismology can provide useful information about the chemical evolution of the Universe because β Cep stars, pulsating in modes of low radial order and periods between about $2 - 7$ hours, are ideal for determining the interior structure and composition of stars around 10

$M_\odot$—precursors of type II supernovae.

3.2.7. Miras and Semiregular Variables

Miras and semiregular variables (M giants) are the coolest and most luminous KASC targets, representing advanced evolutionary stages of low- and intermediate-mass stars such as the Sun. Ground-based photometry has shown many of these stars to have complicated multi-mode oscillations on timescales ranging from several hundred days down to ten days and probably shorter (Wood 2000; Tabur et al. 2009). The oscillations are strongly coupled to important, but still poorly understood mechanisms, such as convection and mass loss.

The uninterrupted coverage and unprecedented precision of *Kepler* photometry will allow the first application of asteroseismology to M giants. We anticipate the first exciting results in this field after the first year of observations, while the most intriguing theoretical questions will require the full time span of the project. By measuring the oscillation frequencies, amplitudes and mode lifetimes we will challenge stellar models and examine the interplay between convection and the κ mechanism, and the roles of both in exciting and damping the oscillations (Xiong & Deng 2007). We also hope to shed light on the mysterious Long Secondary Periods phenomenon (Nicholls et al. 2009) and to search for chaotic behavior and other non-linear effects that arise naturally in these very luminous objects (Buchler, Kolláth & Cadmus 2004).

3.3. Oscillating Stars in Binaries and Clusters

One of the goals of the asteroseismology program is to model the oscillation frequencies of stars in eclipsing binaries. In order to find such stars in the *Kepler* field of view, a global variability classification treating all KASC stars observed in Q0 and Q1 was performed with the methodology by Debosscher et al. (2009). This revealed hundreds of periodic variables all over the H-R Diagram, among which occur stars with activity and rotational modulation in the low-frequency regime, Cepheids, RR Lyr stars, and multiperiodic nonradial pulsators (Blomme et al. 2009). More than 100 new binaries were also identified. About half of those are likely to be ellipsoidal variables while the other half are eclipsing binaries, several of which have pulsating components. One example for a case unknown prior to launch is shown in Figure 8, where we see pulsational behavior which is typical for gravity modes in a slowly pulsating B star (Degroote et al. 2009) in an eclipsing system with a period of about 11 days with both primary and secondary eclipses. Examples of pulsating red giants

in eclipsing binaries are clear in early *Kepler* data (Hekker et al. 2009), and discussed for the above case of KOI-145. Eclipsing binaries with pulsating components not only provide stringent tests of stellar structure and evolution models, they also offer the opportunity to discover planets through changes of the pulsation frequencies due to the light travel time in the binary orbit (Silvotti et al. 2007). For these reasons, pulsating eclipsing binaries are prime targets within KASC.

Star clusters are Rosetta Stones in stellar structure and evolution. Stars in clusters are believed to have been formed from the same cloud of gas at roughly the same time, leaving fewer free parameters when analyzed as a uniform ensemble, which allows stringent tests of stellar evolution theory. Seismic data enable us to probe the interior of models, and thus should allow us to test aspects of stellar evolution that cannot be addressed otherwise, such as whether or not the sizes of convective cores in models are correct. Asteroseismology of star clusters has been a long sought goal that holds promise of rewarding scientific return. In particular, the advantages of asteroseismology for clusters are that, unlike estimates of colors and magnitudes, seismic data do not suffer from uncertainties in distance or extinction and reddening.

There are four open clusters in the *Kepler* field of view, NGC 6791, NGC 6811, NGC 6866 and NGC 6819. In Figure 9 we show a color-magnitude diagram of stars in NGC 6819 and point out the relative flux variation of four stars along the giant branch. Initial data from *Kepler* have allowed the first clear measurements of solar-like oscillations in cluster stars by Stello et al. (2010). The oscillations of the stars are clear even without any further analysis. The power in the oscillations changes with luminosity and effective temperature as expected from ground-based and early space-based observations of nearby field stars. The data further enable us to determine cluster membership by lining up the power spectra of the observed stars in order of their apparent magnitude. We have detected several possible non-members in this manner, which previously all had high membership probabilities ($P > 80\%$) from radial-velocity measurements.

While the currently available data from *Kepler* are for stars on the giant branch of the clusters, future observations will also provide data for the subgiants and main-sequence stars. Having seismic data for stars at various stages of evolution will allow us to have independent constraints on the cluster age. Since stars in a cluster are coeval and have the same metallicity, the process of modelling detailed seismic data of these stars will allow us to test the various physical processes that govern stellar evolution.

4.   Summary

The phenomenal promise of the *Kepler Mission* to invigorate stellar astrophysics through the study of stellar oscillations is clearly being realized. The unprecedented combination of temporal coverage and precision is sure to provide new insights into many classical variable stars, to increase by more than two orders of magnitude the number of cool main-sequence and subgiant stars observed for asteroseismology and to completely revolutionize asteroseismology of solar-like stars.

Facilities: The Kepler Mission

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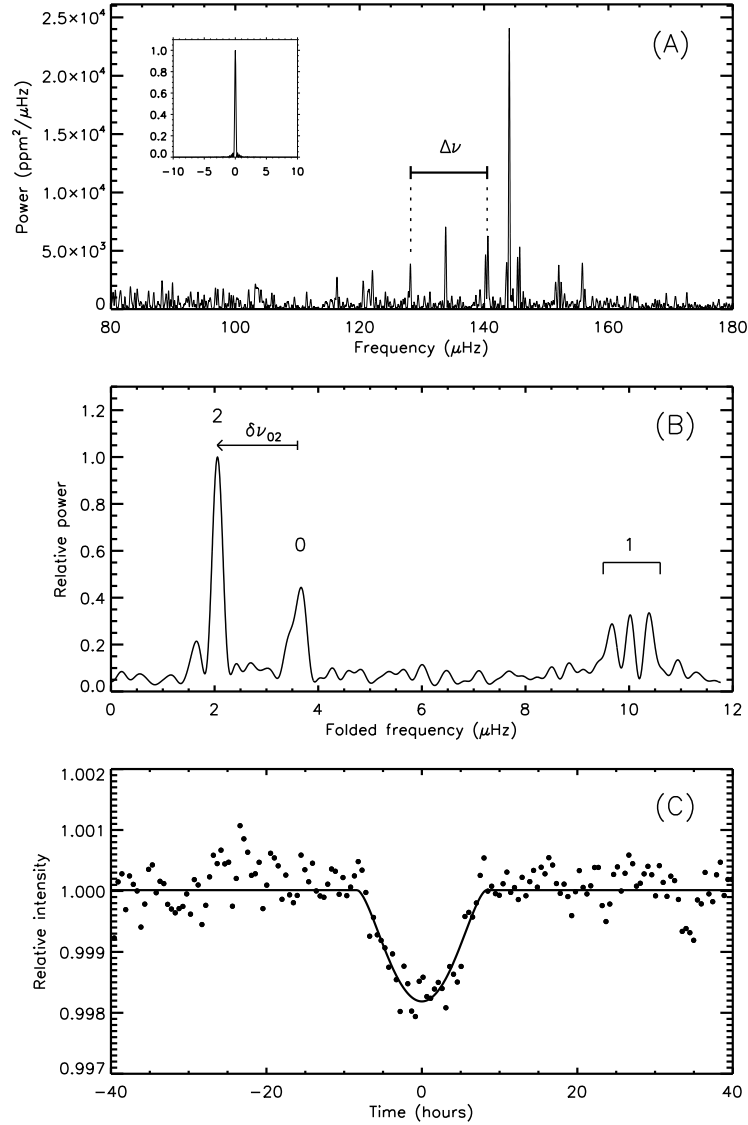
Fig. 1.— Panel A shows the power spectrum for KOI-145 with the signature of solar-like oscillations in a red giant. This shows the power between 80 and 180 μHz with an indication of the large separation parameter, $\Delta\nu$ between two consecutive $l = 1$ modes. The inset shows the nearly perfect spectral window provided by these *Kepler* data. Panel B shows the result of folding the power spectrum by $\Delta\nu$ which clearly shows the resulting distribution of $l = 2$, 0, and 1 (from left) modes corresponding to the relation given in Eq. 1. Panel C shows part of the time series for KOI-145 and a superposed 'transit' light curve solution. Assuming the stellar radius as implied by the asteroseismology of R = 5.99 $\pm$ 0.15 R$_\odot$ results in a transiting object size of $\sim$ 0.4 R$_\odot$, well removed from the planetary realm. The eclipsing object is likely an M-dwarf star.
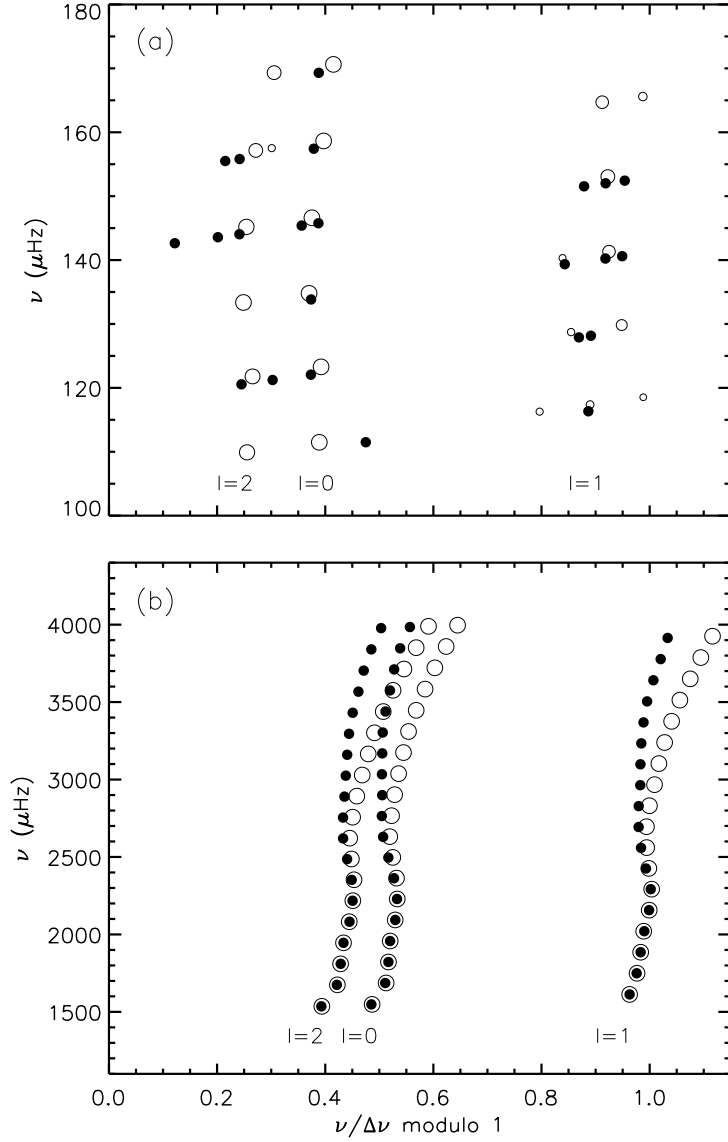
Fig. 2.— The distribution of low-angular-degree p modes in a so-called échelle diagram, in which individual oscillation frequencies are plotted against the frequencies modulo the average large frequency spacing, and with the abscissa scaled to the $\Delta\nu$ units. Panel a shows results for KOI-145. The filled symbols are the observed frequencies and the open symbols show frequencies from a model in the grid calculated by Stello et al. (2009), with symbol sizes proportional to a simple estimate of the amplitude (see Christensen-Dalsgaard, Bedding & Kjeldsen 1996). Panel b shows frequencies for the Sun, with filled symbols indicating observed frequencies (Broomhall, A.-M., et al. 2009), while open symbols show the frequencies of Model S (Christensen-Dalsgaard et al. 1996).
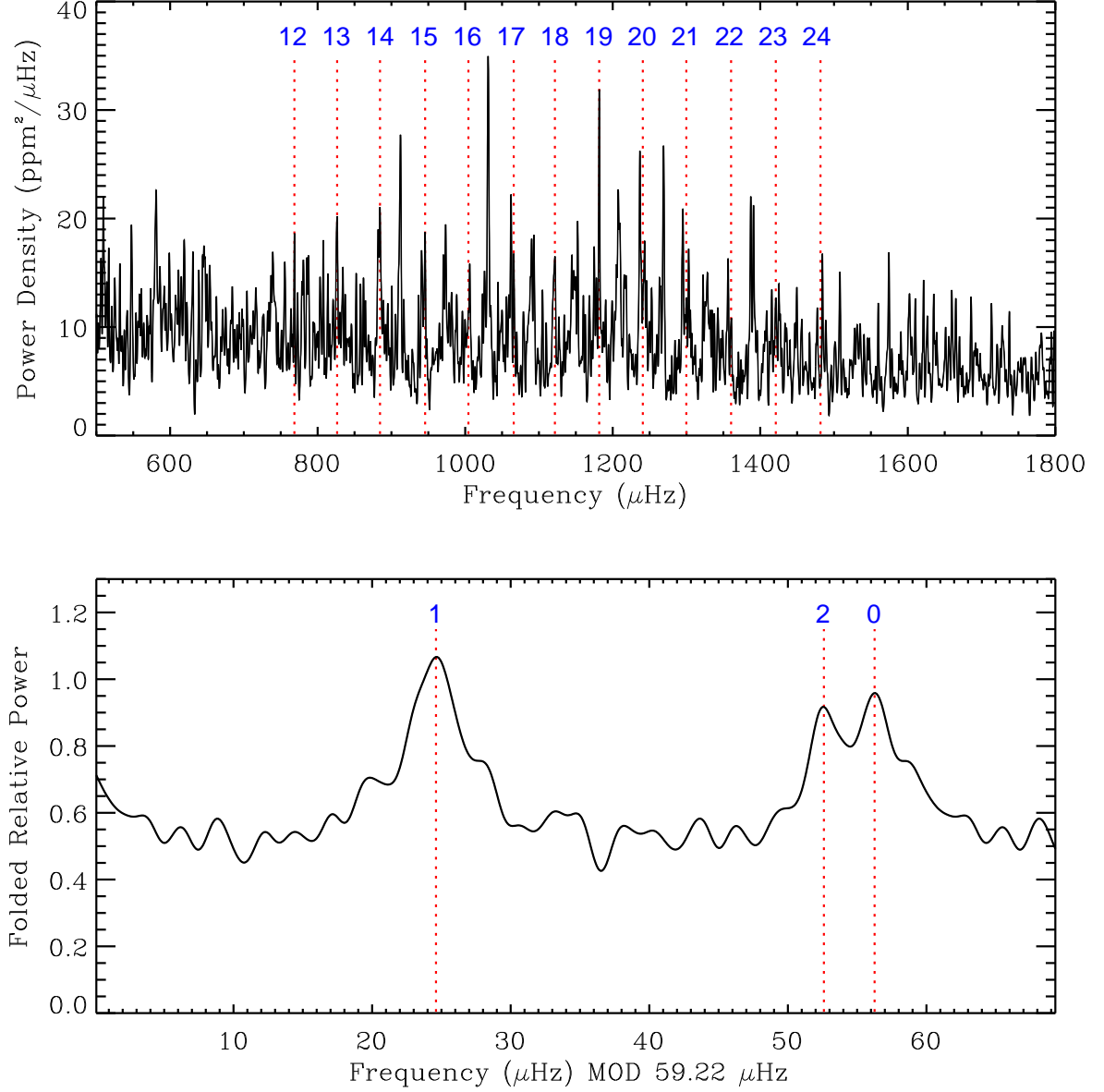
Fig. 3.— The upper panel shows the power spectrum for the previously known HAT-P-7 host star based on *Kepler* Q0 and Q1 data. The marked modes are the radial, $l = 0$ frequencies labelled with inferred radial order n. The lower panel shows the power spectrum folded by $\Delta\nu$ with the $l = 1, 2$, and 0 ridges (from left) as indicated.
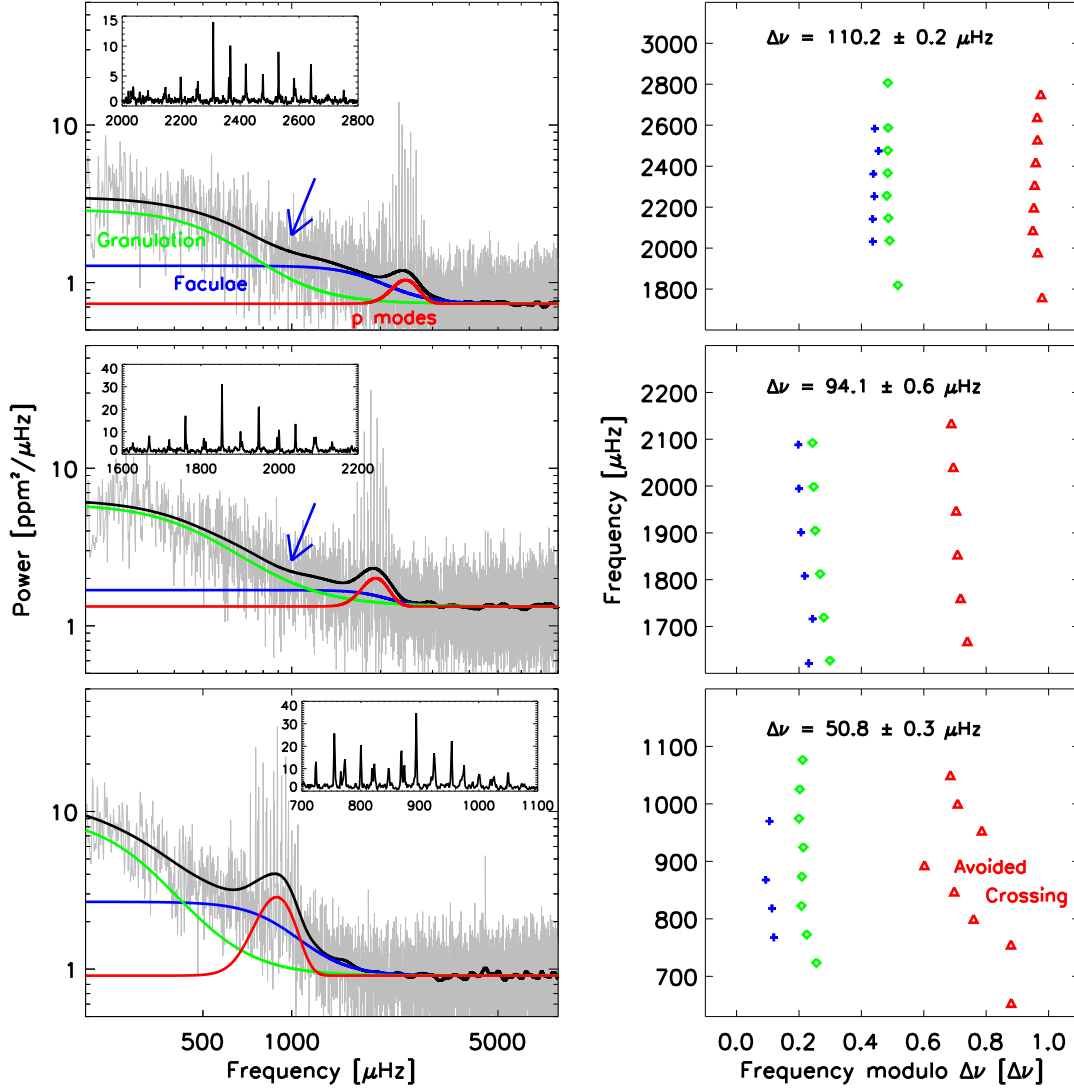
Fig. 4.— Left-hand panels: Frequency-power spectra of *Kepler* photometry of three solar-like stars (grey) over $200 - 8000$ μHz. The thick black lines show the result of heavily smoothing the spectra. Fitted estimates of the underlying power spectral density contribution of p modes, bright faculae and granulation as labelled in the top left panel are also shown; these are color coded red, blue and green respectively in the on-line version. These components sit on top of a flat contribution from photon shot noise. The arrows mark a kink in the background power that is caused by the flattening toward lower frequencies of the facular component. The insets show the frequency ranges of the most prominent modes. Right-hand panels: So-called échelle plots of individual mode frequencies. Individual oscillation frequencies have been plotted against the frequencies modulo the average large frequency spacings (with the abscissa scaled to units of the large spacing of each star). The frequencies align in three vertical ridges that correspond to radial modes ($l = 0$, diamonds), dipole modes ($l = 1$, triangles) and quadrupole modes ($l = 2$, crosses).
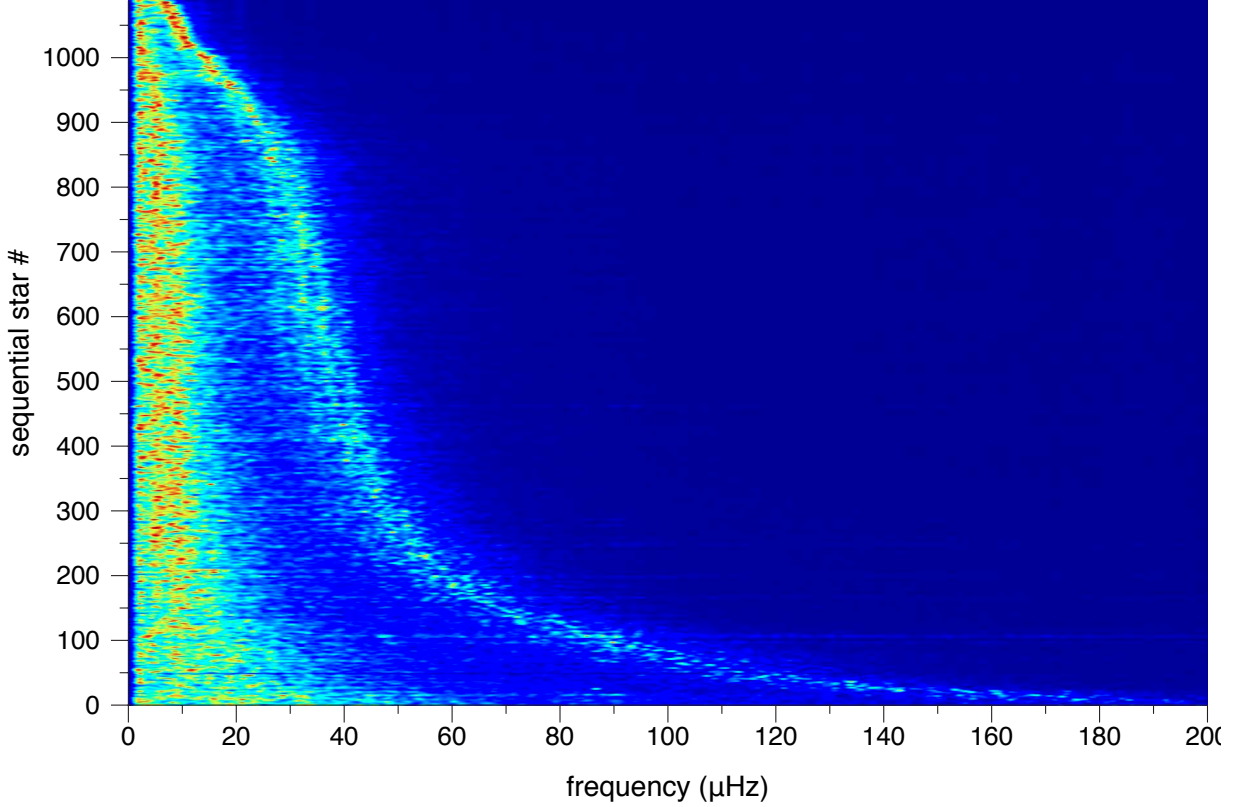
Fig. 5.— *Kepler* red giant power spectra have been stacked into an image after sorting on ν_{max} for the oscillation peak. Larger stars, with lower frequency variations are at the top. The ever-present slow variations due to stellar granulation are visible as the band at the left, generally in the 2 - 10 μHz range. The curve from top left to bottom right traces the oscillations. Low-mass, low-luminosity giants are clearly visible here with $\nu_{\mathrm{max}} > 100$ μHz (Bedding et al. 2010). The slope of the curve is a measure of how fast the evolutionary stage is, the more horizontal the faster, although selection effects for the sample also need to be taken into account. The bulk of the giants are He-burning stars with a ν_{max} around 40 μHz. The fact that the top right part of the figure is so uniformly dark illustrates how little instrumental noise there is for *Kepler*. By contrast the low-Earth orbit for CoRoT imposes extra systematic noise in the general domain of 160 μHz contributing to its lack of results on these smaller, more rapidly varying and lower-amplitude red giants.
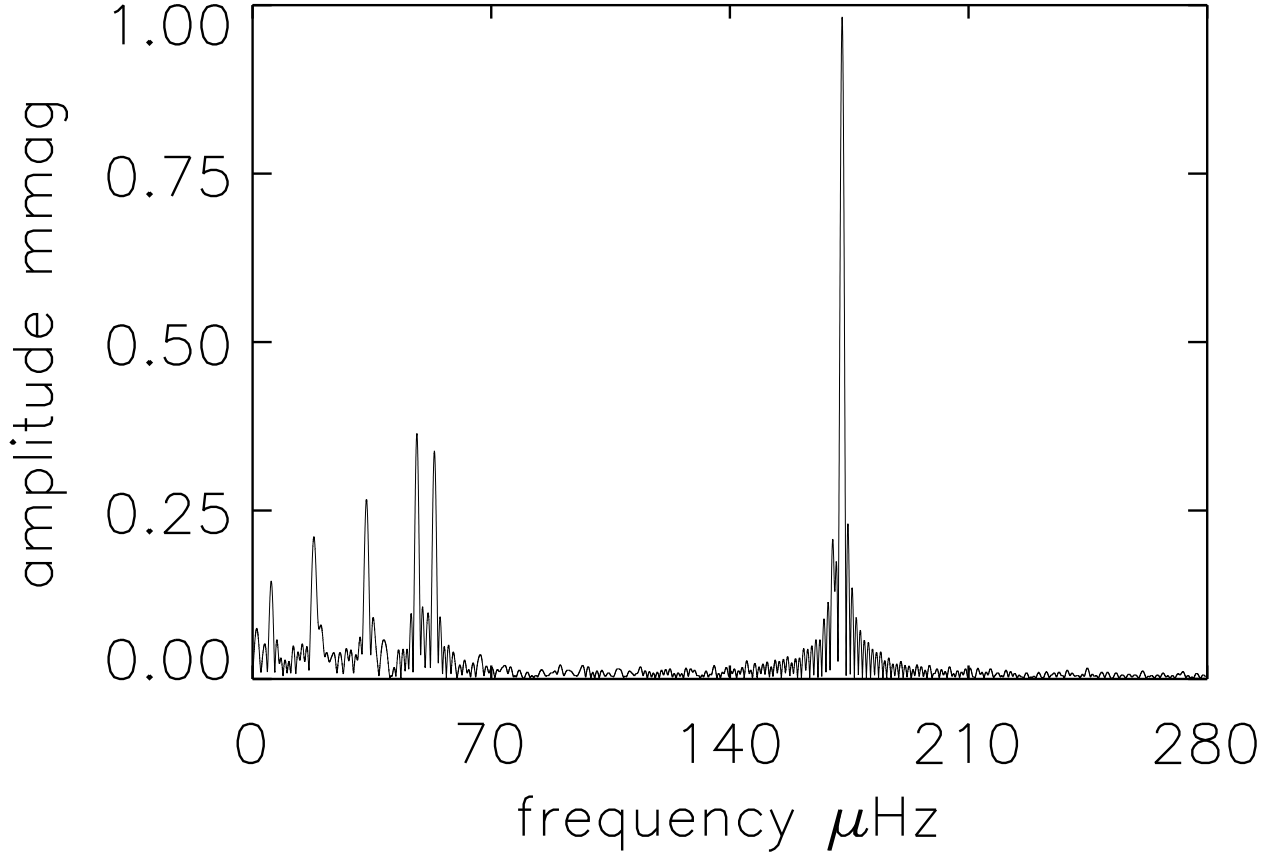
Fig. 6.— Amplitude spectrum of the δ Sct – γ Dor star hybrid KIC 09775454 where the g-mode pulsations are evident in the $0 - 70\,\mu$Hz range and the p-mode pulsation is evident at $173\,\mu$Hz ($P = 96\,$min). There are further frequencies in the δ Sct range that are not seen at this scale. The amplitude spectrum has a high frequency limit just below the Nyquist frequency of $283\,\mu$Hz for LC data. In the range $70 - 140\,\mu$Hz there are no significant peaks. The highest noise peaks have amplitudes of about $20\,\mu$mag; the noise level in this amplitude spectrum is about $5\,\mu$mag.
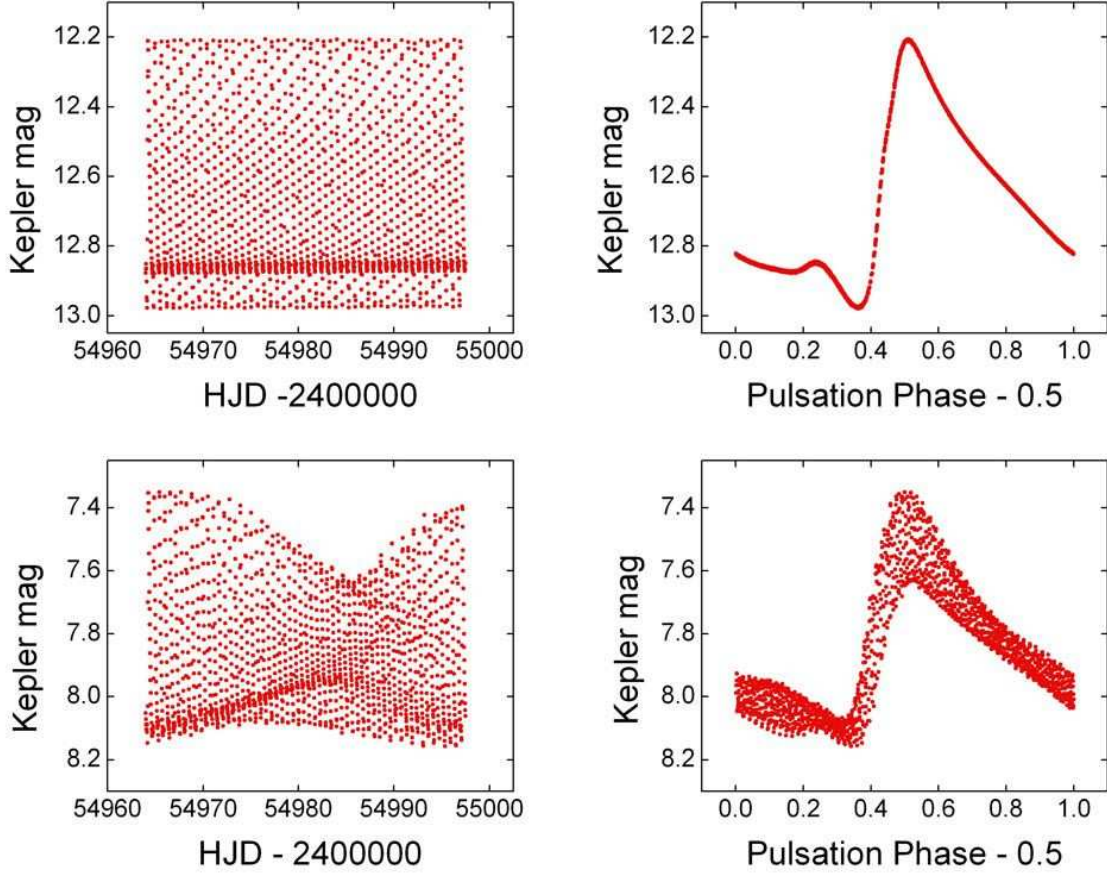
Fig. 7.— The upper panel shows direct and folded Q1 light curves for the non-modulated RR Lyrae star NR Lyrae, while the lower panel illustrates the rapid evolution of oscillation wave form present in RR Lyrae itself – characteristic of many RR Lyrae stars monitored with *Kepler*.
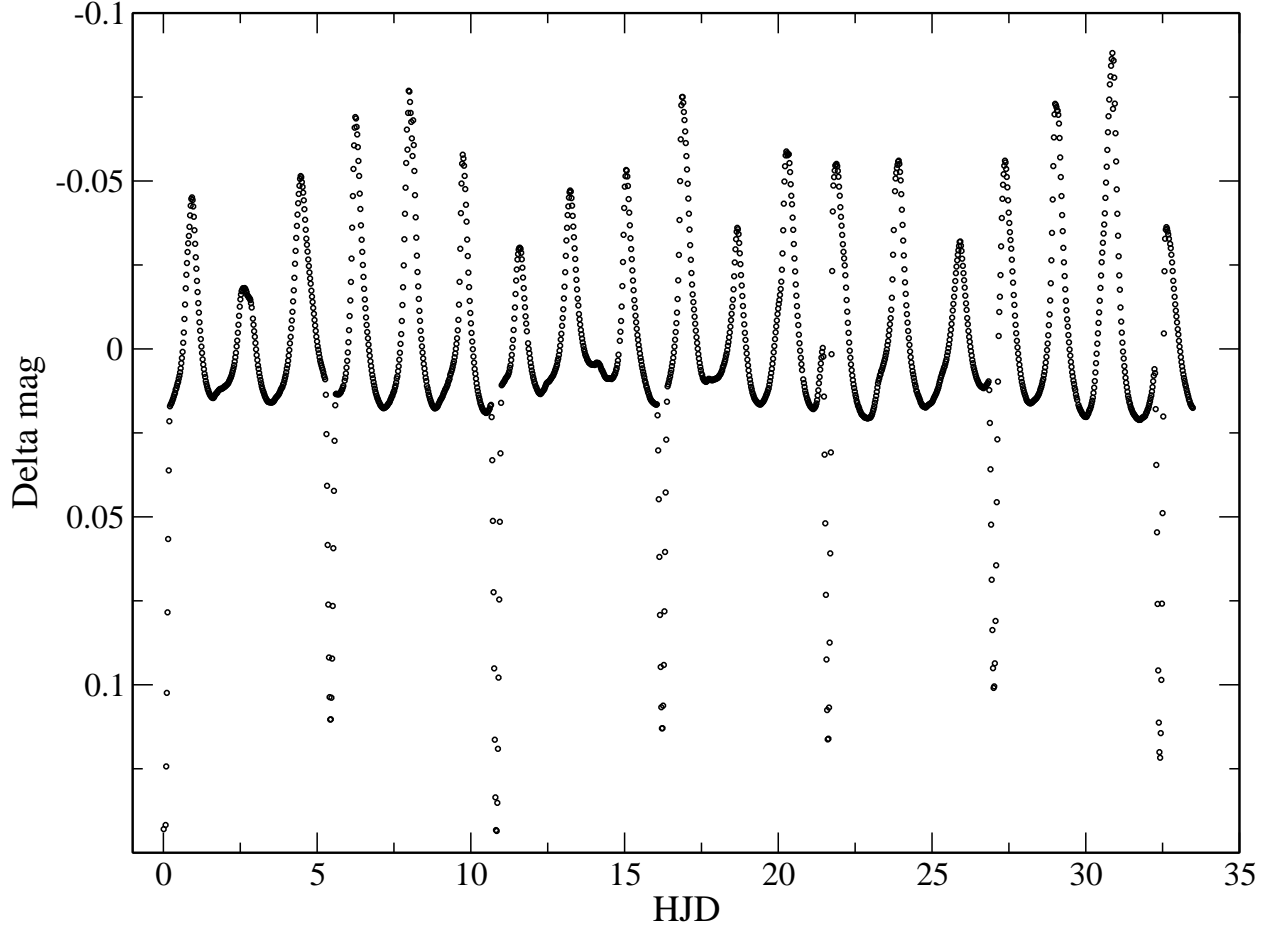
Fig. 8.— Time series over Q1 of the slowly pulsating B-star, KIC-11285625, which shows both large amplitude multi-periodic pulsations, and primary and secondary eclipses. With the addition of ground-based radial-velocity studies and the exquisite *Kepler* light curve elucidating the broad range of phenomena visible here, this is likely to become one of the more important asteroseismic targets.
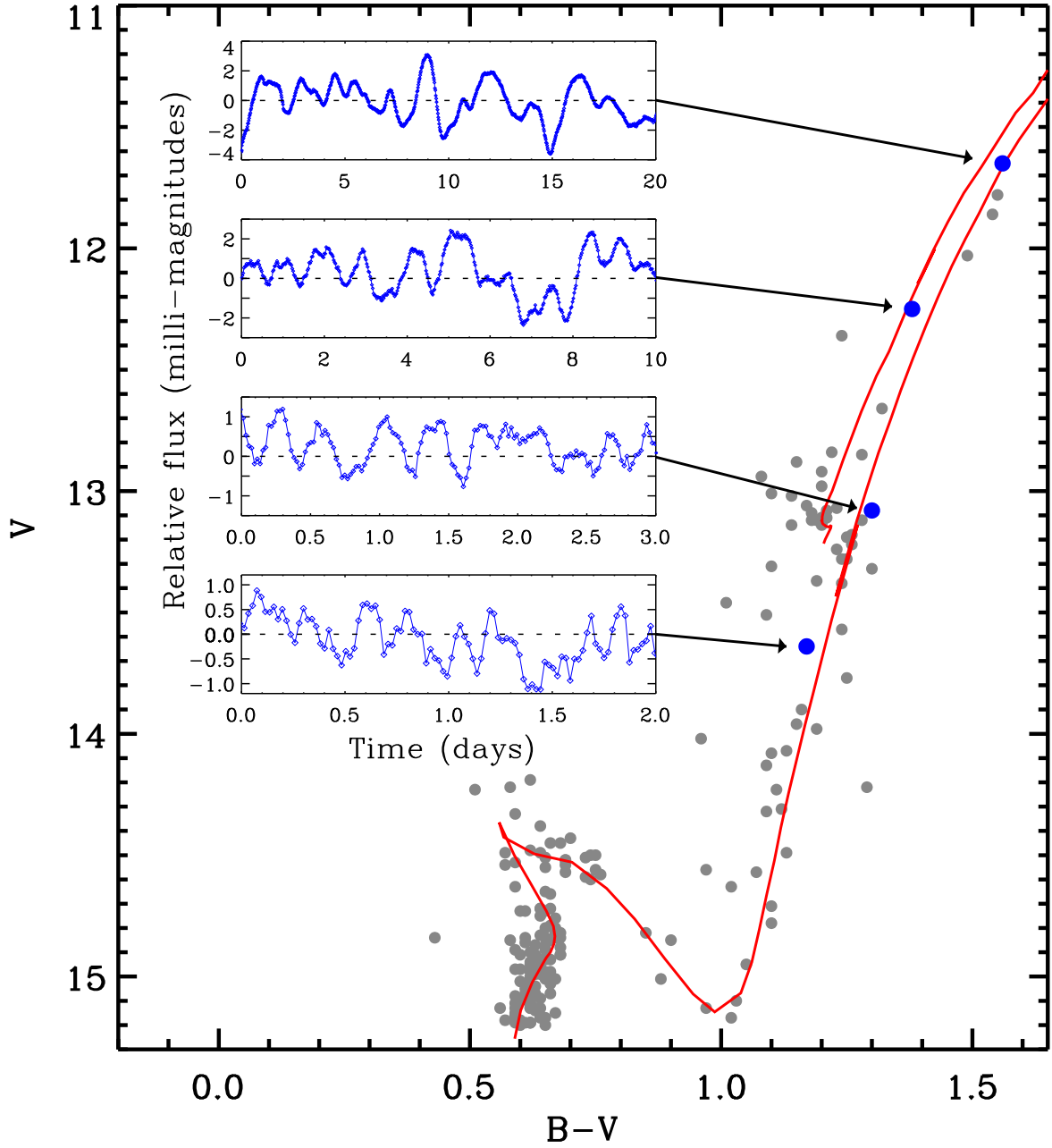
Fig. 9.— Color-magnitude diagram for NGC 6819. The grey points show stars that have high radial-velocity probabilities from Hole et al. (2009). The curve (red in on-line version) is a solar metallicity, 2.5 Gyr isochrone of Marigo et al. (2008). The larger, dark-grey (blue) points are four of the *Kepler* targets; we show the time series of their brightness fluctuation in the insets. As can be seen from the inset, the timescale of the oscillations decreases with increasing apparent magnitude of the stars.